Chapter 12
Who Killed the All-Electric Car?

Electric cars (EV) seem like the best thing since sliced bread. The liquid fuels they don't burn make more oil available for heavy-duty trucks, ships, and planes. It should not escape our notice that there are very few electric trucks and no electric ships or planes. Later in this book, we'll explore those possibilities, but for now, suffice to say they aren't so easily electrified (Long 2011).

Inventors began making batteries (and fuel cells) circa 1800, yet there are still very few all-electric autos. The 2006 documentary film, "Who Killed the Electric Car", blames automakers, the oil industry, the U.S. government, and faults the intelligence of consumers.

But that's not who did it. Drum roll … It was the battery! Not much suspense in so quickly revealing that, but it's still a good story. The real mystery, however, is not *who* did it, but *why* batteries aren't powerful enough, despite 215 years of research. The lead–acid battery hasn't changed much since its invention in 1859. Li-ion batteries hold over two times as much energy by weight as the first commercial batteries sold in 1991 but are nearing their limit. The energy density of other commercial rechargeable batteries had risen only six-fold since the lead–nickel batteries from the horse and buggy era of over a century ago (Van Noorden 2014a).

Yet, hope springs eternal. A better battery has always been just around the corner:

- 1901: "A large number of people … are looking forward to a revolution in the generating power of batteries, and it is the opinion of many that the long-looked-for, lightweight, high capacity battery will soon be discovered" (Hiscox 1901).
- 1901: "Demand for a proper automobile battery is so crying that it soon must result in the appearance of the desired [battery]. Everywhere in the history of industrial progress, invention has followed close in the wake of necessity" (Electrical Review #38. May 11, 1901. McGraw-Hill).
- 1974: "The consensus among EV proponents and major battery manufacturers is that a high-energy, high power-density battery—a true breakthrough in electrochemistry—could be accomplished in just five years" (Machine Design).
- 2015—An Internet search for "battery breakthrough" gets 38,700 results, including: *Secretive Company Claims Battery Breakthrough, 'Holy Grail' of*

A.J. Friedemann, *When Trucks Stop Running*,
Energy Analysis, DOI 10.1007/978-3-319-26375-5_12

Battery Design Achieved, Stanford breakthrough might triple battery life, A Battery That 'Breathes' Could Power Next-Gen Electric Vehicles, 8 Potential EV and Hybrid Battery Breakthroughs.

So Why Isn't There a Better Battery?

That black box may look simple, but inside is a churning chaos of complex electrochemistry as the battery surges between being charged and discharged over and over again, which is hard on a battery. Recharging is supposed to put Humpty Dumpty back together again, but over time the metals, liquids, gels, chemicals, and solids inside clog, corrode, crack, crystallize, become impure, leak, and break down.

The vehicle battery palette is limited to the 118 elements in the periodic table. Most can be ruled out because they're radioactive (29), inert noble gases (6), don't conduct electricity, are rare earth or platinum group metals (23), too toxic (9), not found on earth (2), too scarce, too expensive, or too heavy.

The laws of physics have imposed theoretical maximum energy limits on batteries due to the properties of the elements in the periodic table (Zu et al. 2011). The highest possible energy density would be an almost 6-V Lithium–Fluorine battery (Li/F_2). But despite decades of research, no Li-F battery exists because it is very toxic, not rechargeable, unstable, unsafe, and inefficient, the solvents and electrolytes can't handle the voltage, and ultimately lithium fluoride crystallizes and stops conducting electricity.

The second highest, Li–air (Li/O_2), theoretically has an energy density approaching gasoline, but in practice might be twice as good as current Li-ion batteries. They're still experimental, with low power, poor cyclability, and need pure O_2, which requires an oxygen tank. A prototype is probably over 30 years away (NRC 2015b).

It is not easy to make a better battery. Here are just some of the qualities required to achieve the holy grail of a better battery:

1. Small and lightweight to take up less space and give vehicles a longer range
2. High specific energy density (energy stored per unit of weight and unit of volume) to deliver energy for hours and give vehicles a longer range
3. High power density for acceleration and capture of regenerative braking energy
4. Ability to be recharged thousands of times (cycle life) while retaining 80 % of energy storage capacity in real-world driving so that the battery will last as long as the vehicle: 10–15 years.
5. Ability to be recharged fast, in 10 min or less, rather than overnight
6. Not harmed by overcharging, undercharging, or over-discharging
7. Reliable and robust, able to tolerate vibration, shaking, and shocks
8. Made from inexpensive, common, sustainable, and recyclable materials
9. Safe: doesn't explode, catch on fire, and has no toxic materials

10. Doesn't self-discharge when not in use
11. Performs well in both low and high temperatures
12. Needs minimal to no maintenance
13. Much cheaper than the battery packs now that run about $450 per kWh, or $35,000 for a 78 kWh battery

Basically, the ideal battery would be alive and able to self-heal, secrete impurities, and recover from abuse, like cartoon characters who are back to normal seconds after explosions, falling off of cliffs, or sawn in half. That's what the world needs, the Wiley Coyote battery!

Pick Any Two, there is no "One Size Fits All." Batteries are a lot like the sign "Pick any two: Fast, Cheap, or Good." Although li-ion batteries are ahead of lead–acid, nickel–cadmium, and nickel–metal hydride due to their high-energy storage, none of the Li-ion chemistries so far offer an ideal combination of energy density, power capability, durability, safety, and cost (NRC 2013). On top of that, lithium batteries lose charge even when idle, and don't perform well in cold and hot temperatures.

You always give up something. Battery chemistry is complex. Anode, cathode, electrolyte, and membrane separator materials must all work together. Every time you improve one thing, you might harm other essential features. Higher energy densities come from reactive, less stable chemicals that often result in non-rechargeable batteries, are susceptible to impurities, or catch on fire. Storing more energy may lower the voltage.

Battery testing takes time. Every time a change is made, dozens of parameters need to be retested to make sure that the improvement didn't break or lessen other essential properties. Even with accelerated testing, it takes a long time to see if the new battery will last at least 7 to 15 years. First, each battery cell is tested, then a module containing multiple (battery) cells, and finally the battery pack.

"You have to optimize too many different things at the same time" according to Venkat Srinivasan at Lawrence Berkeley National Laboratory (Service 2011).

Conflicting demands. For example, "If you want high [energy] storage, you can't get high power," said M. Stanley Whittingham, director of the Northeast Center for Chemical Energy Storage. "People are expecting more than what's possible."

Be skeptical of battery breakthrough announcements. It typically takes 10 years to improve an *existing* type of battery, and it's expensive. You need chemists, material scientists, chemical and mechanical engineers, electrochemists, computer, and nanotechnology researchers (Borenstein 2013). Then, another five years to develop, test, and manufacture a new car that uses the new battery.

Van Noorden (2014b) at *Nature* magazine reported on why a recent, highly hyped aluminum battery breakthrough may never appear in your phone or car. Not mentioned were a few obstacles such as having only one-fifth the energy of li-ion batteries, that lab prototypes were so tiny that when scaled up for real use, the aluminum battery may not recharge as quickly, and the much larger electrodes might crack. Even if it clears these hurdles, commercial aluminum batteries could be 15 years away. Van Noorden said the story of batteries is one of the small startups promising way more than they can deliver in order to get investment money (Van Noorden 2014a). A good example is Envia Systems, which raised $17 million from GM and other investors on a battery that never panned out (LeVine 2015).

Shortening the decade-long development process. "We need to leapfrog the engineering of making of batteries to find the next big thing," said Vince Battaglia, a Lawrence Berkeley National Lab battery scientist.

Incremental improvements won't electrify cars and energy storage fast enough (DOE 2007). Scientists need to understand the laws of battery physics better to make a big leap. To do that, researchers need to be able to observe what's going on inside a battery at an atomic scale in **femtoseconds (0.000000000000001 s)**, build nanoscale tubes and wires to improve ion flow, and devise complex models and computer programs that use this data to predict what might happen when some aspect of a battery is changed.

The laws of physics and properties of elements in the periodic table mean there's only so much rechargeable electrochemical energy you can theoretically cram into a black box. No matter what you do, that always will be orders of magnitude less than petroleum (House 2009).

Alas, there are additional limits. The energy provided by battery (cells) is cut in half within a battery pack as energy is lost from cell to module to battery management system. Battery packs consist of modules with batteries overseen by a battery management system that uses energy to monitor and cool cells down. Elaborate control systems prevent a shorter battery life by making sure all cells have the same thermal history and protect against too fast charging or discharging. Each cell's voltage, temperature, and internal resistance is monitored. The cooling system prevents thermal runaway or fatal destruction of cells at temperatures over 120 °F (NPC 2012).

Further energy is drained by air-conditioning, heating, lighting, dashboard displays, music, and GPS, all of them reducing the range.

Lithium is famously flammable, but many battery types can catch on fire, so the battery pack is encased in steel for protection. A significant amount of weight and volume also come from the monitoring and cooling systems. In the end, the battery pack is so heavy, that for every pound of the battery pack, up to 1.5 pounds of structural support for the body and chassis is required. Because of this, an electric vehicle with a 300 mile range might weigh three times more than a conventional car (Shiau et al. 2009; Wagner et al. 2010).

All-Electric Autos

Electric vehicles are not likely to take off until they have at least a 200 mile range and cost considerably less than the $71,000 Tesla S, which can go 265 miles with an 85 kWh battery pack. Tesla's battery is 3.1–5.3 times larger than competitors, whose vehicles travel 62–93 miles on 16–27 kWh batteries and it costs from $25,700 to $43,300 (plugincars 2015).

To achieve greater ranges will require batteries with three times greater energy densities at one-third the current cost per kWh (NPC 2012). What are the prospects for that? Researchers think lithium-ion battery energy density might be improved by 30 % at best (Van Noorden 2014a, b). EVs are also held back because there are only 53 million garages (Lowenthal 2008) in the U.S. for 253 million vehicles (Hirsch 2015).

So far, most of the increases in the driving range of all-electric cars come from the use of lightweight materials, aerodynamics, and tires with less rolling resistance.

Early adopters are buying all-electric vehicles, but the masses are hanging back. One reason: The time it takes to recharge an all-electric vehicle battery is a non-starter. Overnight, or even an hour wait, won't cut it. Unless batteries can be developed that can be recharged in 10 min or less without degradation, cars will be limited largely to local travel in an urban or suburban environment (NRC 2013). In this respect, electric vehicles are the turtle and gasoline vehicles are the hare. Electric vehicles charge about 1,000 times slower than refueling with gasoline (NAS 2008). To recharge faster than that requires a level 3 charger costing $15,000–$60,000 which would make fast charging of electric vehicles more expensive per mile than gasoline (Hillebrand 2012).

To be competitive in electrified vehicles, the United States also requires a domestic supply base of batteries, and key materials and components such as special motors, transmissions, brakes, chargers, conductive materials, foils, electrolytes, and rare earth metals, most of which come from abroad. The supply chain adds significant costs to making batteries, but it's not easy to shift production to America because electric and hybrid car sales are too few, and each auto maker has its own specifications (NAE 2012).

We may notice a new Tesla, but there aren't that many all-electric vehicles on American roads. At current rates of transition from gasoline to all-electric cars and trucks, with 123,000 electric vehicles sold in 2014 (InsideEVs 2015), it would take over 2000 years to replace the nation's fleet of 253 million vehicles), and require 980 TWh of electricity (25 % of 2008 generation) taking about 15 years to build (Smil 2010). Cost is not a minor impediment. The average income of an electric car owner is $148,158, and of a new gasoline car $83,166, far above the median household of $51,929 (NRC 2015a).

Hybrid battery-gasoline cars have been far more successful, with 3.6 million sold in the U.S., since 2000. Hybrid batteries last much longer than all-electric batteries because they are not discharged deeply, perhaps 30 % of the useable capacity. That gives hybrid batteries a significantly longer life than plug-in electric batteries, which discharges from 70 to 80 % of their capacity for more range, reducing battery life.

In many ways, Americans are spendthrift when it comes to energy. As a nation, we have been willing to spend trillions of dollars fighting multiple wars in the oil mecca of the Mideast. We spend billions per year to protect oil sea lanes and chokepoints. And when it comes to why we buy a particular vehicle, Americans rank fuel efficiency 11th in terms of importance (NRC 2015b, Table 9.4). The vehicles we actually buy reflect that. Until 2007, 85 % of the cars on American roads got less than 22 mpg, and when gas prices dropped in 2014, hybrid sales went down and SUV sales went up.

In the end, it's not just the lack of a better battery but American consumers who are unwilling, or unable to afford energy efficient cars (and light trucks) of any kind.

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